How safe is it to train residents to perform coronary surgery with multiple arterial grafting? Nineteen years of training at a single institution.

Umberto Benedetto PhD, Massimo Caputo MD, Hunaid Vohra MD, PhD, Mustafa Zakkar PhD, Alan Bryan MD, Gianni D Angelini MD.

Bristol Heart Institute, University of Bristol, School of Clinical Sciences, Bristol, UK

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Corresponding Author

Umberto Benedetto MD PhD

Bristol Heart Institute, University of Bristol

Upper Maudlin St, Bristol BS2 8HW

Tel: +44 (0) 117 3422856

Email: umberto.benedetto@bristol.ac.uk

Abbreviations

AF: atrial fibrillation

BITA: bilateral internal thoracic arteries

BMI: Body Mass Index

CABG: coronary artery bypass grafting

COPD: chronic obstructive pulmonary disease

CX: Circumflex artery

GLMM: Generalized linear mixed-effects model

IABP: intraaortic balloon pump

MAG: multiple arterial grafting

MI: myocardial infarction

NYHA: New York Heart Association

LAD: left anterior descending artery

LMD: left main disease

LVEF: left ventricular ejection fraction

PCI: percutaneous coronary intervention

PVD: peripheral vascular disease

RA: radial artery

RCA: right coronary artery

RRT: renal replacement tharapy

sCr: serum creatinine

SV: saphenous vein

SW: sternal wound

NVD: number of vessel disease

LITA: left internal thoracic artery

Central message: A nineteen years training experience at a single institution found, that adequately supervised trainees can perform CABG with multiple arterial grafting without compromising patient safety and long term survival.

Perspective statement: The conflict between trainee education and patient safety, requires surgical training policies to be guided by robust clinical data and high-level evidence. We demonstrated that supervised trainees can effectively perform CABG with multiple arterial grafting without compromising patient safety. These results are expected to promote residents training in multiple arterial grafting.

Abstract

Objective: The learning curve of coronary artery bypass grafting (CABG) with multiple arterial grafting (MAG) is perceived to be associated with increased surgical morbidity and potentially poorer long term outcomes. We compared short term outcomes and long term survival in patients who underwent CABG with MAG performed by attending surgeons or resident trainees at a single institution over a period of 19 years.

Methods: Using our institutional database, we identified 3039 patients undergoing MAG from 1996 to 2015. Of those, 958 (32%) were operated by residents and 2081 (68%) by attending surgeons. Propensity score matching and mixed effect models were used to compare the two groups.

Results: Operative mortality was 0.3% and 0.4% among patients operated by residents and attending surgeons respectively (P=0.71) with no significant differences between the groups in postoperative complications. **After a mean follow-up time of 11±4 years, survival probability at 5,10 and 15 years was 95.1%±0.7% versus 96.4%±0.6%, 87.0%±1.1% versus 87.8%±1.1% and 76.6.%±1.8% versus 77.6%±1.8% in the resident and attending surgeon group respectively. Resident and attending surgeon cases showed comparable risk of death (HR 1.01; 95%CI 0.80-1.28; P=0.92). The equipoise between the two groups was confirmed among cases receiving bilateral internal thoracic arteries only (HR 0.88; 95%CI 0.54-1.43; P=0.61), radial artery (HR 1.22; 95%CI 0.92-1.61; P=0.15) or their combination (HR 0.74; 95%CI 0.33-1.65; P=0.47).**

Conclusions: The present analysis confirms that adequately supervised trainees can perform CABG with multiple arterial grafting without compromising patient safety and long term survival.

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Despite multiple arterial grafting (MAG) including bilateral internal thoracic arteries (BITA) and radial artery (RA) has been consistently shown to improve survival after coronary artery bypass grafting (CABG), it still remains largely underutilized [1-4]. It is disconcerting that only 10% of patients undergoing CABG currently receive a second arterial graft in the United States, approximately 4% with BITA and 6% with RA [5]. Moreover, among 1541 procedures performed in the SYNTAX trial and registry, 97.1% included a single arterial conduit, while only 22.7% received BITA grafts [6].

The most commonly cited reason for not performing CABG with MAG, is the learning curve, perceived to be associated with increased surgical morbidity and potentially poorer long term outcomes [7]. This often result in lack of exposure to MAG procedures during cardiothoracic training program [7]. Moreover, the current intense professional and public scrutiny of cardiac surgeons' results creates a hostile environment not conducive to trainees' exposure to MAG.

Here, we compared the short and long term outcomes of CABG with MAG performed by attending surgeons or resident trainees at the Bristol Heart Institute over a period of 19 years.

Methods

Study design

The study was conducted in accordance with the principles of the Declaration of Helsinki. The local audit committee approved the study, and the requirement for individual patient consent was waived. This study was a registry-based analysis involving patients with multivessel coronary artery disease who underwent elective isolated CABG using at least two arterial conduits from April 1996 to April 2015, at the Bristol Heart Institute, United Kingdom. We retrospectively analysed prospectively collected data from the National Institute for Cardiovascular Outcomes Research (NICOR) registry for audit and quality assessment of adult cardiac surgery in the United Kingdom. Reproducible cleaning algorithms were applied to the database, which are regularly updated as required. Briefly, duplicate records and non-adult cardiac surgery entries were removed; transcriptional discrepancies harmonized; and clinical conflicts and extreme values corrected or removed. The data are returned regularly to the local units for validation. Further details and definition of variables are available at http://www.ucl.ac.uk/nicor/audits/adultcardiac/datasets.

Study population

Patients were eligible for inclusion in the study if they had undergone isolated CABG performed by either attending surgeons or residents using at least two arterial conduits in the following configuration: BITA, left internal thoracic artery (LITA) and RA or BITA plus RA with or without additional saphenous vein (SV) grafts. In the present series, the RA was considered only in case of target stenosis ≥75% and it was used as a free graft proximally connected to the ascending aorta or as a "y "graft attached to the internal thoracic artery. The internal thoracic artery was used as a pedicle graft that remained proximally connected to its respective subclavian artery (in situ) or as a free graft proximally connected to other internal thoracic artery as a "y" graft. **Exclusion criteria were: 1) cases performed by non-attending**

surgeons who had completed their training program; 2) no information available on the primary surgeon status; and 3) LITA not used.

Training Program

The Bristol Heart Institute is a regional cardiac surgical center and part of the UK national training program. The UK cardiothoracic training program is conducted over a 6-year period, and admission to it requires successful completion of a 2-year basic surgical training program. Two to three National Training Numbers were allocated to our unit at any time during the study period. In addition, 4 to 6 clinical research or service clinical fellows completed the surgical rota. Seniority level of trainees with official training numbers was defined according to year of training in the UK specialist program in cardiothoracic surgery (Calman year 1–6). For trainees who did not have an official UK training number (research or clinical fellows), the level of experience was reviewed and assigned according to equivalent criteria. A resident case was retrospectively defined as a case in which the cardiothoracic resident performed the entire surgical procedure. A supervised operation performed by a resident was defined as one in which the attending surgeon was scrubbed in and acted as first assistant. An unsupervised operation was defined as one in which the resident had reviewed the case and planned the surgical strategy with the attending surgeon who was not scrubbed in. The decision to have a resident case was at the discretion of individual attending surgeons. There was no formal agreement on a minimum number of cases to be performed by the resident during his/her training program. The patients operated upon by the resident were selected by assessing their suitability for training taking into account the urgency of the operation and their co-morbidities, the quality of the coronary arteries and the number of grafts required.

Training in MAG progressed to gradually increasing levels of complexity including y graft and off-pump multiple arterial grafting.

Study Endpoints

Short-term outcomes analysed were: re-exploration for bleeding, need for sternal wound reconstruction, postoperative cerebrovascular accident (CVA) (defined as any confirmed neurologic deficit of abrupt onset that did not resolve within 24 hours), postoperative renal replacement therapy (RRT), need for postoperative intra-aortic balloon pump (IABP), in-hospital mortality, the occurrence of any of above complications and length of stay was compared between the two groups. The incidence of incomplete revascularization (IR), defined as at least one diseased primary arterial territory not grafted was also investigated.

Long term outcome investigated was all-cause mortality. This is considered the most robust and unbiased index in cardiovascular research because no adjudication is required, thus avoiding inaccurate or biased documentation and clinical assessments [9]. Information about post-discharge mortality tracking was available for all patients (100%) and was obtained by linking the institutional database with the National General Register Office.

Pre-treatment variables

The effect of procedure performed by Resident versus Attending surgeon on outcomes of interest was adjusted for the following pre-treatment variables including: age, gender, body mass index (BMI); New York Heart Association grade III or IV; prior myocardial infarction (MI) within 30 days, previous percutaneous coronary intervention (PCI); active smoking; diabetes mellitus (DM) on oral treatment or on insulin; chronic obstructive pulmonary disease (COPD); current smoking; serum creatinine ≥200 mmol/l, previous cerebrovascular accident (CVA); peripheral vascular

disease (PVD); preoperative atrial fibrillation (AF); left main disease (LMD); number of vessel diseased; left ventricular ejection fraction (LVEF) between 30% and 49%; LVEF less than 30%; non elective admission, emergent/salvage operation; cardiogenic shock; preoperative IABP and eras of surgery. Predicted risk was assessed using Euroscore according to the following definition [10]: low risk as 0-2 points (0.8% expected mortality), medium risk as 3-5 points (3.0% expected mortality), and high risk as > 5 points (11% expected mortality)

Statistical analysis

Categorical variables were presented as frequencies and percentages and continuous variables were expressed as mean±standard deviation. Multiple imputation was used to address missing data (https://cran.r-project.org/package=Amelia). Rubin's method [11] was used to combine results from each of 3 imputed data sets. To control for measured potential confounders in the data set, a propensity score (PS) was generated for each patient from a multivariable logistic regression model based on pre-treatment covariates as independent variables with procedure performed by resident versus attending surgeon as a binary dependent variable [12] **(Supplementary Table 1)**. Pairs of patients operated by resident versus attending surgeon were derived using greedy 1:1 matching with a calliper of width of 0.2 standard deviation of the logit of the PS (http://CRAN.Rproject.org/package=nonrandom). The quality of the match was assessed by comparing selected pre-treatment variables in propensity score– matched patients using the standardized mean difference (SMD), by which an absolute standardized difference of greater than 10% is suggested to represent meaningful covariate imbalance. **To account for the hierarchical clustering of cases by resident and attending pairs, generalized mixed models were used whereas random intercepts for matching sets were modeled. Generalized linear mixed-effects model was used for short term outcomes. (https://cran.r-**

project.org/package=lme4) **was used for short term outcomes. Mixed effect Cox regression was used to investigate the treatment effect on survival (**https://CRAN.R-project.org/package=coxme**). Time-segmented analysis was used to account for different hazard phases during follow-up [13]. The hazard function was used as a guide to determine approximate time points for the end of the early hazard phase and the beginning of the late phase (**http://CRAN.R-project.org/package=muhaz**). To account for individual attending surgeon effect on outcomes and resident case selection (certain attending surgeons were more likely to allow residents to perform MAG procedures), a second random effect including attending surgeon identification number was added to the model. The intercept for random effect (excess risk) was estimate by using its standard deviation. Integrated log likelihood test was used to test the random effect.** Subgroup analysis was also conducted according to arterial graft configuration adopted (BITA or RA grafting separately). Finally the effect of procedure performed by resident versus attending on in-hospital mortality and late mortality was investigated according to different stages of cardiothoracic training program early stage (year 1 and 2), intermediate stage (years 3 and 4), final stage (years 5 and 6). Unsupervised and supervised cases were also compared. All p-values <0.05 were considered to indicate statistical significance. All statistical analysis was performed using R Statistical Software (version 3.2.3; R Foundation for Statistical Computing, Vienna, Austria).

Results

Study population

We identified 3039 patients for the final analysis who underwent isolated CABG with MAG during the study period **(Supplementary Figure 1).** Of those, 958 (32%) were operated by residents and 2081 (68%) by attending surgeons. **A total of 22 attending surgeons were identified during the study period. There was a large variability in number of MAG cases** performed by individual attending surgeons and relative rate of resident cases (Supplementary Table 2). Identification of residents performing the procedure was not reported in the majority of cases (735, 76%). Information regarding the stage of training program was available for 340/958(35%) resident cases (early=21; intermediate =128; final =191). Information regarding the supervision by attending surgeon was available for 395/958(41%) resident cases with 338 supervised and 57 unsupervised resident cases. Among unsupervised resident cases, 48 were performed by a resident at final stage of training and 3 by a resident at intermediate stage of training.

Patients characteristics distribution before and after PS matching are summarized in Table 1. Overall, attending surgeons operated on patients with a higher burden of comorbidities and more likely to have 3 vessel disease and left main disease. Moreover, resident cases were more likely to be performed during the early years (Figure 1). Burden of comorbidities and gradually increased over the time with a concomitant decrease in number of cases performed by residents. (Supplementary Table 3). A similar trend was also observed in non-MAG cases (Supplementary Figure 2). After PS matching, 958 matched pairs were obtained and the two groups were comparable for all pre-treatment variables including the extension of coronary artery disease (SMD<10%, Figure 2).

Intraoperative data.

Intraoperative data in the matched groups is reported in Table 2. Resident cases received the same number of grafts and the incidence of incomplete revascularization was comparable between the two groups. Rate of off-pump surgery was higher among attending surgeon cases and x-clamp time and cardiopulmonary bypass time was higher among resident cases. Arterial grafts configuration was also different between the two groups: BITA usage was higher among resident cases while RA usage was higher among attending surgeon cases.

Operative outcomes

Table 3 summarizes postoperative outcomes in the matched cohort. No significant differences were observed between the two groups. The 3 deaths in the resident group all occurred in patients receiving the RA as additional conduit to the ITA. In two cases, off-pump surgery was performed. One death occurred with an unsupervised resident at last-stage of training program, the second death occurred with a supervised resident at final-stage and in one case information on resident status was not available.

Survival

In the matched cohort, mean follow-up time was 11±4 years. Survival probability at 5,10 and 15 years was 95.1%±0.7% versus 96.4%±0.6%, 87.0%±1.1% versus 87.8%±1.1% and 76.6.%±1.8% versus 77.6%±1.8% in the resident and attending surgeon group respectively (Figure 3). The instantaneous risk of death (the hazard function) was found to have 2 hazard phases. The first was a declining hazard phase from the time of operation throughout nearly the first 30 months (early hazard). It then gave way to an increasing hazard phase beyond 30 months (late hazard, Supplementary Figure 3). Resident and Attending surgeon cases showed comparable risk of death during both the early (HR 1.24; 95%CI 0.64-2.42; P=0.50) and the late phase (HR 1.01; 95%CI 0.80-1.28; P=0.92). When the clustering effect due to individual surgeon was added to the model, the two groups were still comparable in terms of early (HR 1. 22: 95%CI 0.63-2.38; P=0.57) and late (HR 1. 04: 95%CI 0.80-1.33; P=0.79). The excess risk for each attending surgeon (the random effect) had a standard deviation of 0.40 and 0.47 for early and late phase (P=1 and P=0.003). Therefore ~15% of attending surgeons had the risk late death of 1.6 times the norm and a similar fraction had lower risk thus suggesting a modestly large attending surgeon effect.

Resident cases were not associated with higher risk of late death in case of early stage of training (HR 1.11; 95%CI 0.27-4.67; P=0.88), intermediate stage (HR 0.78;95%CI 0.41-1.48; P=0.45) and final stage (HR 1.20;95%CI 0.72-2.01; P=0.47; Figure 4). Finally, the equipoise of survival rates between the two groups persisted when we included either supervised (HR 1.05; 95%CI 0.70-1.59; P=0.79) or unsupervised (HR 0.81; 95%CI 0.30-2.19; P=0.68; Figure 5) cases. The equipoise between the two groups in terms of late mortality was confirmed among cases receiving BITA only (HR 0.88; 95%CI 0.54-1.43; P=0.61), LITA plus RA (HR 1.22; 95%CI 0.92-1.61; P=0.15) or the combination of BITA and RA grafting (HR 0.74; 95%CI 0.33-1.65; P=0.47) and among off-pump (HR 1.13; 95%CI 0.83-1.55; P=0.42) and on pump (HR 0.96; 95%CI 0.70-1.37; Figure 5). Finally the two groups presented similar late survival when the analysis was stratified according to low risk (Euroscore 0-2: HR 0.96; 95%CI0.69-1.34; P=0.84), intermediate risk (Euroscore 3-5: HR 0.96; 95%CI 0.67-1.36; P=0.82) and high risk (Euroscore 6 plus: HR 0.94; 95%CI 0.48-1.83; P=0.87; Figure 5).

Discussion

The main finding of this study was that MAG can be safely performed by cardiac surgical residents. Early morbidity was particularly and survival rate up to 15 years were comparable to those observed in patients operated by attending surgeons.

Although the use of additional arterial grafts has been shown to be associated with better outcomes including prolonged survival [1-4], CABG with MAG remains underutilized [5,6]. The learning curve has been cited as the most common reason for not performing MAG [6], questioning whether this procedure should be at all part of a cardiothoracic training program. Performing MAG is undoubtedly technically demanding and patient's safety should always be a concern when training young surgeons. The effect of training on clinical outcome after cardiac surgery has been the subject of previous publications [14-17]. However, to the best of our knowledge, this is the first study which compared outcomes in patients undergoing CABG with MAG performed by residents versus attending surgeons **and we found that the two groups had comparable short term outcomes and long term survival. We noticed that residents were more likely to use BITA while the use of RA was more common among cases performed by attending surgeons. This difference may be partially explained by the better quality of coronary anatomy of resident cases more suitable for BITA grafting. Unfortunately information regarding the quality of native coronary arteries was not available in this retrospective study. However, our subgroup analysis confirmed the equipoise between residents and attending surgeons in performing MAG regardless the graft selection.** MAG performed by resident was also shown to be safe during both on pump and off pump procedures. Finally stage of training program did not significantly impact of late survival. However, it should be noted that in UK, the training program in cardiothoracic surgery is preceded by a surgical core program which provides basic surgical skills training. In the present analysis, there were only few cases performed by resident without supervision and we cannot draw any final conclusion. In many institutions, trainees are preferentially allocated lower-risk and non-urgent CABG cases, so as not to compromise patient safety [18]. The same trend was found in the present analysis and the increase in patient risk profile in more recent years translate into a lower relative volume of resident cases. However, **subgroup analysis based on Euroscore risk classes confirmed that resident and attending surgeons were comparable in performing MAG regardless patient risk profile. Interestingly, using a mixed model we found a significant effect of individual attending surgeon on late mortality regardless the procedure was performed by resident or not. These findings support the hypothesis that other factors may contribute to the safety and efficacy demonstrated by residents such as quality of attending surgeon supervision [19]**. Indeed, in their analysis of >4000 CABG procedures, Elbardissi and colleagues [20] found that the cumulative experience of a consultant-trainee pairing and their familiarity with one another were more significant predictors of operative outcomes than was individual surgeon experience. Similarly our findings support the hypothesis that trainees can safely perform CABG with MAG in the context of a well-structured training program and appropriate supervision.

The present analysis has several limitations. First, it is a retrospective, observational report. Propensity technique can adjust only for measurable and included variables and we cannot exclude a selection bias based on non-measurable "eye-ball" in favour of cases performed by residents. **Patients operated upon by the resident were selected by assessing their suitability for training taking into account not only the urgency of the operation and their comorbidities but also the quality of the coronary arteries. This information was not available for the present analysis. Furthermore, the training usually progresses to gradually increasing levels of complexity and responsibility according to the surgical abilities of the resident. The present analysis could not address whether or not the residents are truly trained on the procedures. Information regarding resident identity was largely missing and we could not analyse its random effect. We stratified our analysis according to stage of training but variation of ability and experience can occur within the same stage.** Moreover, cases that were initially assigned to trainees may have required part of the procedure to be performed by the attending surgeon in the event of unexpected intraoperative complications or difficulties. Although this confounding could theoretically have biased our analysis toward a null value, it provides a more real-world clinical assessment of a surgical training program. **To support our conclusions, we repeated the analysis in the cohort of non-MAG patients. By comparing 3556 matched pairs, we found that resident non-MAG cases were associated with comparable short-term outcomes (Supplementary**

Table 4) and survival when compared to non-MAG attending surgeon cases (HR 0.85;95%CI 0.71-1.13; Supplementary Figure 4).

In conclusion, the present analysis confirms that **MAG exposure during residency is safe without compromising outcomes when adequately supervised by experienced attending surgeons.** Hands-on experience in the operative setting is essential for trainees to develop both the technical skills and clinical judgment required to independently use multiple arterial conduits. Given the perceived conflict between trainees' education and patient safety, it is imperative for surgical training policies to be guided by robust clinical data and high-level evidence.

References

1. Tranbaugh RF, Lucido DJ, Dimitrova KR, Hoffman DM, Geller CM, Dincheva GR et al. Multiple arterial bypass grafting should be routine. J Thorac Cardiovasc Surg. 2015;150:1537-44
2. Shi WY, Hayward PA, Tatoulis J, Rosalion A, Newcomb AE, Fuller JA et al. Are all forms of total arterial revascularization equal? A comparison of single versus bilateralinternal thoracic artery grafting strategies. J Thorac Cardiovasc Surg. 2015;150:1526-33
3. Medalion B, Mohr R, Ben-Gal Y, Nesher N, Kramer A, Eliyahu S et al. Arterial coronary artery bypass grafting is safe and effective in elderly patients. J Thorac Cardiovasc Surg. 2015;150:607-12
4. Benedetto U, Montecalvo A, Kattach H, Amrani M, Raja SG; Harefield Cardiac Outcomes Research Group. Impact of the second internal thoracic artery on short- and long-term outcomes in obese patients: a propensity score matched analysis. J Thorac Cardiovasc Surg. 2015;149:841-7
5. Head SJ, Börgermann J, Osnabrugge RL, Kieser TM, Falk V, Taggart DP, et al. Coronary artery bypass grafting: Part 2--optimizing outcomes and future prospects. Eur Heart J. 2013;34:2873-86.
6. Mohr FW, Morice MC, Kappetein AP, Feldman TE, Ståhle E, Colombo A, et al. Coronary artery bypass graft surgery versus percutaneous coronary intervention in patients with three-vessel disease and left main coronary disease: 5-year follow-up of the randomised, clinical SYNTAX trial. Lancet. 2013;381:629-38.
7. Catarino PA, Black E, Taggart DP. Why do UK cardiac surgeons not perform their first choice operation for coronary artery bypass graft? Heart. 2002;88:643-4

8. **Mastrobuoni S, Gawad N, Price J, Chan V, Ruel M, Mesana TG, et al.Use of bilateral internal thoracic artery during coronary artery bypass graft surgery in Canada: The bilateral internal thoracic artery survey. J Thorac Cardiovasc Surg. 2012;144:874-9.**
9. Lauer MS, Blackstone EH, Young JB, Topol EJ. Cause of death in clinical research: time for a reassessment? J Am Coll Cardiol. 1999;34:618–20
10. **Nashef SA, Roques F, Michel P, Gauducheau E, Lemeshow S, Salamon R. European system for cardiac operative risk evaluation (EuroSCORE). Eur J Cardiothorac Surg. 1999;16:9-13.**
11. **D.B. Rubin. Multiple Imputation for Nonresponse in Surveys. J Wiley & Sons, New York (1987)**
12. Austin PC. A tutorial and case study in propensity score analysis: an application to estimate the effect of in-hospital smoking cessation counseling on mortality. Multivariate Behav Res, 2011;46:119–151.
13. Myers WO, Blackstone EH, Davis K et al. CASS Registry long term surgical survival. Coronary Artery Surgery Study. J Am Coll Cardiol. 1999;33:488-98.
14. Virk SA, Bowman SR, Chan L, Bannon PG, Aty W, French BG et al. Equivalent outcomes after coronary artery bypass graft surgery performed by consultant versus trainee surgeons: A systematic review and meta-analysis.J Thorac Cardiovasc Surg. 2016;151:647-654
15. **Bakaeen FG, Sethi G, Wagner TH, Kelly R, Lee K, Upadhyay A, Thai H, Juneman E, Goldman S, Holman WL. Coronary artery bypass graft patency: residents versus attending surgeons. Ann Thorac Surg. 2012;94:482-8**

16. Murzi M, Caputo M, Aresu G, Duggan S, Angelini GD. Training residents in off-pump coronary artery bypass surgery: a 14-year experience. J Thorac Cardiovasc Surg. 2012;143:1247-53

17. Almassi GH, Carr BM, Bishawi M, Shroyer AL, Quin JA, Hattler B et al. Resident versus attending surgeon graft patency and clinical outcomes in on-versus off-pump coronary artery bypass surgery. J Thorac Cardiovasc Surg. 2015;150:1428-35

18. Jones DA, Gallagher S, Rathod K, Jain AK, Mathur A, Uppal R, et al. Clinical outcomes after myocardial revascularization according to operator training status: cohort study of 22,697 patients undergoing percutaneous coronary intervention or coronary artery bypass graft surgery. Eur Heart J. 2013;34:2887-95.

19. Fallon WF Jr, Wears RL, Tepas JJ III, Maull KI, Angood PB, Champion HR, et al. Resident supervision in the operating room: Does this impact on outcome? J Trauma. 1993;35:556-61.

20. Elbardissi AW, Duclos A, Rawn JD, Orgill DP, Carty MJ. Cumulative team experience matters more than individual surgeon experience in cardiac surgery. J Thorac Cardiovasc Surg. 2013;145:328-33.

Table 1. Baselines characteristics before and after propensity score matching

		Resident		Attending (all)		SMD	Attending (matched)		SMD
Overall		958		2081			958		
Age	<60	541	56.5%	998	48.0%	-17%	522	54.5%	0%
	60-69	324	33.8%	762	36.6%		338	35.3%	
	70-79	89	9.3%	282	13.6%		92	9.6%	
	≥80	4	0.4%	39	1.9%		6	0.6%	
Female	No	859	89.7%	1843	88.6%	-4%	861	89.9%	1%
	Yes	99	10.3%	238	11.4%		97	10.1%	
BMI	<18.5	3	0.3%	4	0.2%	-8%	3	0.3%	-1%
	18.5-24.9	195	20.4%	417	20.0%		198	20.7%	
	25-29.9	488	50.9%	1017	48.9%		483	50.4%	
	30-34.9	230	24.0%	497	23.9%		216	22.5%	
	≥35	42	4.4%	146	7.0%		58	6.1%	
NYHA III-IV	No	742	77.5%	1618	77.8%	1%	743	77.6%	0%
	Yes	216	22.5%	463	22.2%		215	22.4%	
MI within 30 days	No	844	88.1%	1713	82.3%	16%	846	88.3%	0%
	Yes	114	11.9%	368	17.7%		112	11.7%	
PCI	No	913	95.3%	1978	95.1%	1%	908	94.8%	-2%
	Yes	45	4.7%	103	4.9%		50	5.2%	
Smoking	No	805	84.0%	1744	83.8%	-1%	802	83.7%	-1%
	Yes	153	16.0%	337	16.2%		156	16.3%	
DM orally treated	No	886	92.5%	1912	91.9%	2%	887	92.6%	0%
	Yes	72	7.5%	169	8.1%		71	7.4%	
DM on insulin	No	902	94.2%	1965	94.4%	1%	901	94.1%	0%
	Yes	56	5.8%	116	5.6%		57	5.9%	
sCr≥200mmol/l	No	953	99.5%	2065	99.2%	-3%	952	99.4%	-1%
	Yes	5	0.5%	16	0.8%		6	0.6%	

COPD	No	919	95.9%	1992	95.7%	1%	912	95.2%	-4%
	Yes	39	4.1%	89	4.3%		46	4.8%	
CVA	No	939	98.0%	2025	97.3%	-5%	940	98.1%	1%
	Yes	19	2.0%	56	2.7%		18	1.9%	
PVD	No	899	93.8%	1933	92.9%	-4%	899	93.8%	0%
	Yes	59	6.2%	148	7.1%		59	6.2%	
AF	No	937	97.8%	2034	97.7%	0%	937	97.8%	0%
	Yes	21	2.2%	47	2.3%		21	2.2%	
NVD	1	21	2.2%	31	1.5%	-13%	21	2.2%	1%
	2	320	33.4%	584	28.1%		325	33.9%	
	3	617	64.4%	1466	70.4%		612	63.9%	
LMD	No	754	78.7%	1547	74.3%	-10%	742	77.5%	-3%
	Yes	204	21.3%	534	25.7%		216	22.5%	
LVEF 30%-49%	No	839	87.6%	1700	81.7%	-16%	832	86.8%	-2%
	Yes	119	12.4%	381	18.3%		126	13.2%	
LVEF <30%	No	953	99.5%	2029	97.5%	-16%	954	99.6%	2%
	Yes	5	0.5%	52	2.5%		4	0.4%	
Shock	No	958	100.0%	2080	100.0%	3%	958	100.0%	0%
	Yes	0	0.0%	1	0.0%		0	0.0%	
Preop IABP	No	957	99.9%	2069	99.4%	-8%	957	99.9%	1%
	Yes	1	0.1%	12	0.6%		1	0.1%	
Non-elective	No	592	61.8%	1176	56.5%	-11%	568	59.3%	-5%
	Yes	366	38.2%	905	43.5%		390	40.7%	
Emergent/ salvage	No	957	99.9%	2064	99.2%	-11%	957	99.9%	0%
	Yes	1	0.1%	17	0.8%		1	0.1%	
Eras	1996-1999	254	26.5%	307	14.8%	-41%	238	24.8%	1%

	2000-2004	374	39.0%	653	31.4%		383	40.0%	
	2005-2009	230	24.0%	797	38.3%		258	26.9%	
	2010-2015	100	10.4%	324	15.6%		79	8.2%	
Euroscore	0-2	590	61.6%	1198	57.6%		620	64.7%	
	3-5	321	33.5%	699	33.6%		302	31.5%	
	6 plus	47	4.9%	184	8.8%		36	3.8%	

BMI: Body Mass Index; NYHA: New York Heart Association; MI: myocardial infarction; PCI: percutaneous coronary intervention; DM: diabetes mellitus; sCr: serum creatinine; COPD: chronic obstructive pulmonary disease; CVA: cerebrovascular accident; PVD: peripheral vascular disease; AF: atrial fibrillation; NVD: number of vessel disease; LMD: left main disease; LVEF: left ventricular ejection fraction; IABP: intraaortic balloon pump

Table 2. Operative data in the matched cohort

		Resident (N=958)		Attending (N=958)		P_{GLMM}
		n	%	n	%	
Number of grafts	2	350	36.5%	346	36.1%	0.32
	3	471	49.2%	449	46.9%	
	4	128	13.4%	151	15.8%	
	5	9	0.9%	12	1.3%	
Incomplete Revascularization	No	792	82.7%	777	81.1%	0.37
	Yes	166	17.3%	181	18.9%	
LAD grafted	No	20	2.1%	23	2.4%	0.46
	Yes	938	97.9%	935	97.6%	
RCA grafted	No	310	32.4%	314	32.8%	0.84
	Yes	648	67.6%	644	67.2%	
CX grafted	No	192	20.0%	206	21.5%	0.42
	Yes	766	80.0%	752	78.5%	
OPCAB	No	489	51.0%	420	43.8%	<0.001
	Yes	469	49.0%	538	56.2%	
X-time	min(mean,sd)	32±27		25±24		<0.001
CPB-time	min(mean,sd)	54±44		45±41		<0.001
Graft configuration	BITA	332	34.7%	221	23.1%	<0.001
	BITA+RA	91	9.5%	96	10.0%	
	RA	535	55.8%	641	66.9%	

GLMM: Generalized linear mixed-effects model; LAD: left anterior descending artery; RCA: right coronary artery; CX: circumflex artery; OPCAB: off-pump coronary artery bypass grafting; BITA: bilateral internal thoracic arteries; RA: radial artery

Table 3. Postoperative outcomes in the matched cohort.

		Resident N=958		Attending N=958		P_{GLMM}
		n	%	n	%	
Re-exploration for bleeding	No	937	97.8%	935	97.6%	0.76
	Yes	21	2.2%	23	2.4%	
SW reconstruction	No	956	99.8%	955	99.7%	0.65
	Yes	2	0.2%	3	0.3%	
Postoperative CVA	No	951	99.3%	953	99.5%	0.53
	Yes	7	0.7%	5	0.5%	
Postoperative RRT	No	949	99.1%	948	99.0%	0.82
	Yes	9	0.9%	10	1.0%	
Postoperative IABP	No	947	98.9%	947	98.9%	1
	Yes	11	1.1%	11	1.1%	
In-hospital mortality	No	955	99.7%	954	99.6%	0.71
	Yes	3	0.3%	4	0.4%	
Any of above complication	No	911	95.1%	908	94.8%	0.75
	Yes	47	4.9%	50	5.2%	
Length of stay	days(mean, sd)	6.9±4.3		7.1±6.3		0.8

GLMM: Generalized linear mixed-effects model; SW: sternal wound; CVA cerebrovascular accident; RRT: renal replacement therapy; IABP: intraaortic balloon pump.

Supplementary Table 1. Variables included in the propensity score with relative effect size.

Variable	OR	95%CI LL	95%CI UL	P-value
Age* (for 1 year increase)	0.99	0.98	1.00	0.05
Female	0.90	0.69	1.17	0.44
BMI* (for 1 unit increase)	0.99	0.97	1.01	0.18
NYHA III-IV	1.01	0.83	1.23	0.92
MI within 30 days	1.03	0.79	1.34	0.80
PCI	1.37	0.93	1.99	0.11
smoking	0.92	0.73	1.15	0.46
DM orally treated	1.10	0.82	1.49	0.51
DM on insulin	1.18	0.83	1.67	0.35
sCr>200 mmol/l	0.92	0.28	2.57	0.87
COPD	1.28	0.84	1.90	0.23
CVA	0.83	0.47	1.41	0.50
PVD	0.93	0.67	1.29	0.66
AF	1.26	0.72	2.15	0.40
NVD	0.80	0.69	0.94	0.004
LMD	0.90	0.74	1.09	0.28
LVEF 30%-49%	0.61	0.48	0.76	<0.0001
LVEF <30%	0.20	0.07	0.46	<0.0001
Shock	0.00	-	-	0.96
Preop IABP	0.38	0.02	2.05	0.36
Non-elective	0.87	0.73	1.04	0.12
emergent	0.19	0.01	0.96	0.10
Eras* (for 1 year increase)	0.91	0.89	0.93	<0.0001

Entered as continuous variable. OR: Odds ratio; LL: lower limit; UL: upper limit; CI: confidence interval; BMI: Body Mass Index; NYHA: New York Heart Association; MI: myocardial infarction; PCI: percutaneous coronary intervention; DM: diabetes mellitus; sCr: serum creatinine; COPD: chronic obstructive pulmonary disease; CVA: cerebrovascular accident; PVD: peripheral vascular disease; AF: atrial fibrillation; NVD: number of vessel disease; LMD: left main disease; LVEF: left ventricular ejection fraction; IABP: intraaortic balloon pump

Supplementary Table 2. Attending surgeon with number of multiple arterial grafting procedures performed and relative percentage of resident cases

Attending Surgeon	Total N=3039		1996-2004 N=1588		2005-2015 N=1451	
	n	% by Resident	n	% by Resident	n	% by Resident
#1	37	35%	37	35%	0	
#2	817	39%	586	39%	231	38.5%
#3	340	36%	236	40%	104	26.0%
#4	388	44%	279	49%	109	30.3%
#5	4	0%	4	0%	0	
#6	103	51%	102	50%	1	100.0%
#7	26	12%	8	0%	18	16.7%
#8	43	79%	43	79%	0	
#9	23	4%			23	4.3%
#10	245	46%	120	48%	125	44.0%
#11	8	13%	8	12%	0	
#12	275	22%			275	21.5%
#13	119	14%	28	21%	91	12.1%
#14	274	8%			274	8.0%
#15	49	14%	49	14%	0	
#16	246	10%	86	0%	160	15.0%
#17	3	0%			3	0.0%
#18	16	31%			16	31.2%
#19	5	0%			5	0.0%
#20	1	0%			1	0.0%
#21	8	0%			8	0.0%
#22	7	0%			7	0.0%
Missing	2	0%	2	0%	0	

Supplementary Table 3. Baseline characteristics across different eras with relative percentage of resident cases.

		1996-1999			2000-2004			2005-2009			2010-2015			X^2 against Eras
		n	%	% by Resident	n	%	% by Resident	n	%	% by Resident	n	%	% by Resident	
Total		561		45%	1027		36%	1027		22%	424		24%	<0.001
Age	<60	391	70%	44%	549	53%	37%	419	41%	26%	180	42%	33%	<0.001
	60-69	150	27%	49%	382	37%	36%	421	41%	20%	133	31%	21%	
	70-79	20	4%	40%	96	9%	34%	167	16%	23%	88	21%	11%	
	≥80	0	0%		0	0%		20	2%	10%	23	5%	9%	
			0%			0%			0%			0%		
Female	No	511	91%	46%	904	88%	36%	915	89%	22%	372	88%	25%	0.2
	Yes	50	9%	38%	123	12%	37%	112	11%	25%	52	12%	14%	
			0%			0%			0%			0%		
BMI	<18.5	2	0%	50%	2	0%	50%	3	0%	33%	0	0%		<0.001
	18.5-24.9	108	19%	40%	221	22%	38%	195	19%	24%	88	21%	23%	
	25-29.9	341	61%	47%	497	48%	36%	493	48%	22%	174	41%	26%	
	30-34.9	98	17%	49%	247	24%	37%	247	24%	25%	135	32%	22%	
	≥35	12	2%	25%	60	6%	33%	89	9%	16%	27	6%	19%	
			0%			0%			0%			0%		
NYHA III-IV	No	423	75%	46%	743	72%	35%	831	81%	23%	363	86%	25%	<0.001
	Yes	138	25%	43%	284	28%	39%	196	19%	18%	61	14%	15%	
			0%			0%			0%			0%		
MI within 30 days	No	540	96%	46%	952	93%	36%	801	78%	23%	264	62%	26%	<0.001
	Yes	21	4%	38%	75	7%	36%	226	22%	21%	160	38%	19%	
			0%			0%			0%			0%		

PCI	0	561	100%	45%	1003	98%	37%	959	93%	21%	368	87%	23%	<0.001
			0%		24	2%	12%	68	7%	37%	56	13%	30%	
			0%			0%			0%			0%		
smoking	No	455	81%	47%	851	83%	36%	883	86%	22%	360	85%	24%	0.05
	Yes	106	19%	40%	176	17%	38%	144	14%	22%	64	15%	20%	
			0%			0%			0%			0%		
DM orally treated	No	534	95%	46%	952	93%	37%	928	90%	22%	384	91%	23%	0.004
	Yes	27	5%	41%	75	7%	35%	99	10%	25%	40	9%	25%	
			0%			0%			0%			0%		
DM on insulin	No	538	96%	46%	963	94%	36%	964	94%	22%	402	95%	24%	0.3
	Yes	23	4%	39%	64	6%	44%	63	6%	27%	22	5%	9%	
			0%			0%			0%			0%		
sCr≥200mmol/l	No	557	99%	46%	1025	100%	36%	1025	100%	22%	411	97%	23%	<0.001
	Yes	4	1%	0%	2	0%	50%	2	0%	0%	13	3%	31%	
			0%			0%			0%			0%		
COPD	No	549	98%	46%	1001	97%	36%	971	95%	23%	390	92%	23%	<0.001
	Yes	12	2%	25%	26	3%	62%	56	5%	16%	34	8%	32%	
			0%			0%			0%			0%		
CVA	No	551	98%	46%	1008	98%	36%	992	97%	23%	413	97%	24%	0.09
	Yes	10	2%	30%	19	2%	63%	35	3%	6%	11	3%	18%	
			0%			0%			0%			0%		
PVD	No	528	94%	45%	951	93%	37%	967	94%	23%	386	91%	24%	0.1
	Yes	33	6%	58%	76	7%	33%	60	6%	15%	38	9%	16%	
			0%			0%			0%			0%		
AF	No	555	99%	45%	1005	98%	36%	1000	97%	22%	411	97%	24%	0.1
	Yes	6	1%	50%	22	2%	36%	27	3%	26%	13	3%	23%	
			0%			0%			0%			0%		
NVD	1VD	8	1%	38%	13	1%	31%	22	2%	55%	9	2%	22%	0.006
	2VD	165	29%	44%	356	35%	39%	260	25%	24%	123	29%	37%	

	3VD	388	69%	46%	658	64%	35%	745	73%	21%	292	69%	18%	
			0%			0%			0%			0%		
LMD	No	482	86%	46%	779	76%	37%	756	74%	23%	284	67%	24%	<0.001
	Yes	79	14%	41%	248	24%	33%	271	26%	21%	140	33%	22%	
			0%			0%			0%			0%		
LVEF 30-49%	No	473	84%	48%	838	82%	38%	862	84%	23%	366	86%	25%	0.1
	Yes	88	16%	32%	189	18%	30%	165	16%	17%	58	14%	12%	
			0%			0%			0%			0%		
LVEF<30%	No	551	98%	46%	1010	98%	37%	1005	98%	23%	416	98%	24%	0.9
	Yes	10	2%	20%	17	2%	18%	22	2%	0%	8	2%	0%	
			0%			0%			0%			0%		
shock	0	561	100%	45%	1026	100%	36%	1027	100%	22%	424	100%	24%	0.6
			0%		1	0%	0%		0%			0%		
			0%			0%			0%			0%		
Preop IABP	No	560	100%	45%	1025	100%	36%	1027	100%	22%	414	98%	24%	<0.001
	Yes	1	0%	0%	2	0%	0%		0%		10	2%	10%	
			0%			0%			0%			0%		
Non elective	No	355	63%	44%	591	58%	39%	582	57%	24%	240	57%	27%	0.06
	Yes	206	37%	47%	436	42%	32%	445	43%	21%	184	43%	20%	
			0%			0%			0%			0%		
Emergent/salvage	No	559	100%	45%	1020	99%	37%	1022	100%	23%	420	99%	24%	0.6
	Yes	2	0%	0%	7	1%	14%	5	0%	0%	4	1%	0%	
			0%			0%			0%			0%		
Euroscore	0-2	381	68%	46%	588	57%	35%	598	58%	24%	221	52%	32%	
	3-5	163	29%	45%	369	36%	39%	348	34%	22%	140	33%	17%	
	6 plus	17	3%	29%	70	7%	37%	81	8%	14%	63	15%	8%	

BMI: Body Mass Index; NYHA: New York Heart Association; MI: myocardial infarction; PCI: percutaneous coronary intervention; DM: diabetes mellitus; sCr: serum creatinine; COPD: chronic obstructive pulmonary disease; CVA: cerebrovascular accident; PVD: peripheral vascular disease; AF: atrial fibrillation; NVD: number of vessel disease; LMD: left main disease; LVEF: left ventricular ejection fraction; IABP: intraaortic balloon pump

Supplementary Table 4. Short-term outcomes in 3556 matched pairs of patients operated on by Resident versus Attending Surgeon

		Resident		Attending		P_{GLMM}
		N=3556		N=3556		
Re-exploration for bleeding	No	3541	99.6%	3529	99.2%	
	Yes	15	0.4%	27	0.8%	
Sternal wound reconstruction	No	3463	97.4%	3463	97.4%	0.07
	Yes	93	2.6%	93	2.6%	
CVA	No	3498	98.4%	3516	98.9%	0.07
	Yes	58	1.6%	40	1.1%	
RRT	No	3486	98.0%	3482	97.9%	0.58
	Yes	70	2.0%	74	2.1%	
IABP	No	3497	98.3%	3471	97.6%	0.03
	Yes	59	1.7%	85	2.4%	
In-hospital mortality	No	3527	99.2%	3520	99.0%	0.38
	Yes	29	0.8%	36	1.0%	

GLMM: Generalized linear mixed-effects model; SW: sternal wound; CVA cerebrovascular accident; RRT: renal replacement therapy; IABP: intraaortic balloon pump.

Figure Legend

Central picture: Survival in patients undergoing multiple arterial grafting (MAG) operated on by resident versus attending surgeon.

Figure 1. Number of MAG procedures performed by resident and attending surgeon during the study period. (MAG: multiple arterial grafting)

Figure 2. Standardized mean difference before and after matching (BMI: Body Mass Index; NYHA: New York Heart Association; MI: myocardial infarction; PCI: percutaneous coronary intervention; DM: diabetes mellitus; DMO: diabetes mellitus orally treated; sCr: serum creatinine; COPD: chronic obstructive pulmonary disease; CVA: cerebrovascular accident; PVD: peripheral vascular disease; AF: atrial fibrillation; NVD: number of vessel disease; LMD: left main disease; LVEF: left ventricular ejection fraction; IABP: intraaortic balloon pump)

Figure 3. Survival probabilities after MAG performed by residents versus attending surgeons in the matched cohort. (MAG: multiple arterial grafting)

Figure 4. Survival probabilities after MAG performed by residents stratified for stage of training (left) and supervision (right) versus attending surgeons in the matched cohort. (MAG: multiple arterial grafting)

Figure 5. Survival probabilities after MAG performed by residents versus attending surgeons in the matched sample stratified for graft configuration (left), off-pump versus on pump (central) and Euroscore (right). (MAG: multiple arterial grafting; BITA: bilateral internal thoracic artery; RA: radial artery; ES: Euroscore)

Supplementary Figure 1. Study flow chart. (CABG: coronary artery bypass grafting; LITA: left internal thoracic artery)

Supplementary Figure 2. Number of non-MAG (left) and MAG (right) performed by resident and attending surgeon across different eras according to Euroscore risk class. (MAG: multiple arterial grafting)

Supplementary Figure 3. Hazard function in the matched sample

Supplementary Figure 4. Survival probabilities after non-MAG procedures performed by residents versus attending surgeons in 3556 matched pairs. (MAG: multiple arterial grafting).

Video 1. Off-pump multiple arterial grafting using the radial artery